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COMMENT ON ESTIMATING THE SOLAR PROTON ENVIRONMENT THAT MAY AFFECT MARS MISSIONS

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ABSTRACT

Estimates of the energetic proton environment for a Mars mission are generally extrapolated from the solar proton observations at 1 AU. We find that solar particle events may be divided into two general classes. Events dominated by a near-sun injection of particles onto interplanetary magnetic field lines leading to the spacecraft position represent the "classical" solar particle event associated with solar activity. This class of event will scale in radial distance by the classical power law extrapolation. The extended-interplanetary-shock source generates a maximum flux as the shock passes the detection location. This class of event typically generates maximum fluence, but in this case, the flux and fluence will not scale in the classical manner with radial distance. Published by Elsevier Science Ltd on behalf of COSPAR.

INTRODUCTION

The usual method for estimating the energetic proton environment for a Mars mission is to take the solar proton observations at 1 AU (such as modeled by Feynman et al., 1993) and then extrapolate these observations to other radial distances. In these extrapolations it is assumed that the proton flux is confined to a magnetic "flux tube" and the volume of this tube will behave in the classical manner as the radial distance from the sun (which we will designate as R) increases. From this purely geometrical argument, the peak flux extrapolations should behave as a function of R^{-3}, and the fluence extrapolations should behave as a function of R^{-2}. The limited experimental data of measuring the same event at different radial distances generally confirm the utility of this type of radial extrapolation, however with a modified form of the power laws. The working group consensus recommendations for radial extrapolation documented in a JPL report edited by Feynman and Gabriel (1988) were:

> *Flux extrapolations from 1 AU to > 1 AU; use a functional form of $R^{-3.3}$ and expect variations ranging from R^{-4} to R^{-3}.*
>
> *Flux extrapolations from 1 AU to < 1 AU; use a functional form of R^{-3} and expect variations ranging from R^{-3} to R^{-2}.*
>
> *Fluence extrapolations from 1 AU to other distances; use a functional form of $R^{-2.5}$ and expect variations ranging from R^{-3} to R^{-2}.*

In this paper we suggest that these generalizations only apply to specific types of well-connected solar flare associated events and that they do not always apply to the case of general shock accelerated events.

TYPES OF SOLAR PROTON EVENTS

In Figure 1 we have plotted all of the events observed at 1 AU during the last 4 solar cycles (19-22) in which the >30 MeV omni-directional proton fluence observed at the Earth exceeded 10^9 cm^{-2}. These are the very large events that are worrisome for astronaut safety. It becomes apparent from this figure that

there are two distinct classes of events as labeled on the figure. We group the solar proton events into general classes of near-sun injection events and interplanetary shock dominated events. This is similar to the grouping of Reames (1995) who generalized solar proton events into impulsive and gradual events except that this classification was based on the X-ray characteristics of the associated solar flare activity. We will further sub-divide the interplanetary shock dominated events into two sub-classes, regular shock events, and converging shock events.
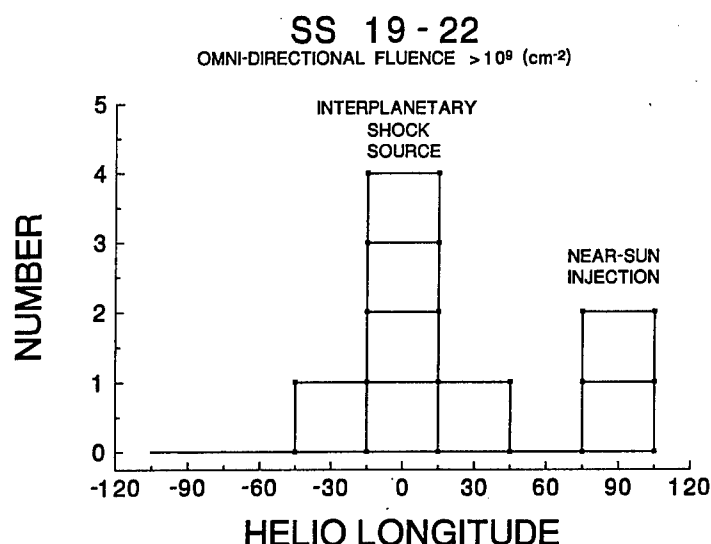
SS 19 - 22
OMNI-DIRECTIONAL FLUENCE >10⁹ (cm⁻²)

Fig. 1. All solar proton events observed at 1 AU during the last 4 solar cycles (19-22) in which the >30 MeV omni-directional proton fluence exceeded 10^9 cm^{-2}.

Near-Sun Injection Events

The near-sun injection events are those that are the result of solar activity on the western hemisphere of the sun near the "favorable propagation position" for field lines connecting to an observer at the Earth. This class covers both the "impulsive" flare associated events and the western heliolongitude fast CME associated events. The impulsive flare associated events presumably have a short lifetime injection source commensurate with the solar flare activity. So the event duration is presumably the injection profile propagated away from the sun at the particle velocity. In the case of a far western heliolongitude CME source, the interplanetary shock is not directed toward the observer and continues to move along its initial direction in space. Even though particle acceleration continues at the shock front, the interplanetary magnetic field (IMF) connection from the portion of the shock front that is perpendicular to the IMF becomes increasingly tenuous and the accelerated particles passing by the observer are primarily those injected along the IMF leading to the observer when the particle acceleration source was close to the sun. This leads to the classic solar proton event having a rapid rise to maximum and then a slower decay. This is the class of event in which the proton flux in magnetic "flux tubes" should scale in the classical manner as the distance from the sun increases as described in the previous section.

An example of this class of event, the proton event that began on 24 October 1989 (associated with solar activity at about 60° west heliolongitude), is illustrated in Figure 2. Even though this is a solar cosmic ray ground-level event, the time integral of the >30 MeV proton flux (i.e. the fluence) for this event is below the 10^9 threshold used for Figure 1. This event is one of the few solar proton events during solar cycle 22 for which there are actual images of the associated coronal mass ejection. This CME is illustrated in Figure 3.
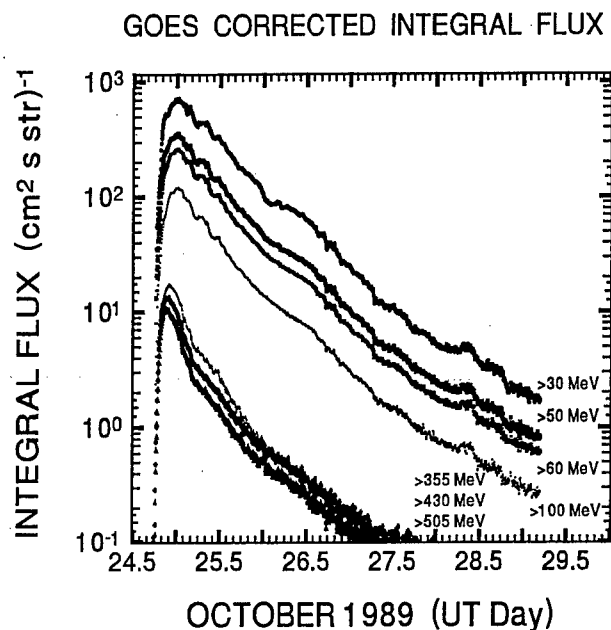
GOES CORRECTED INTEGRAL FLUX
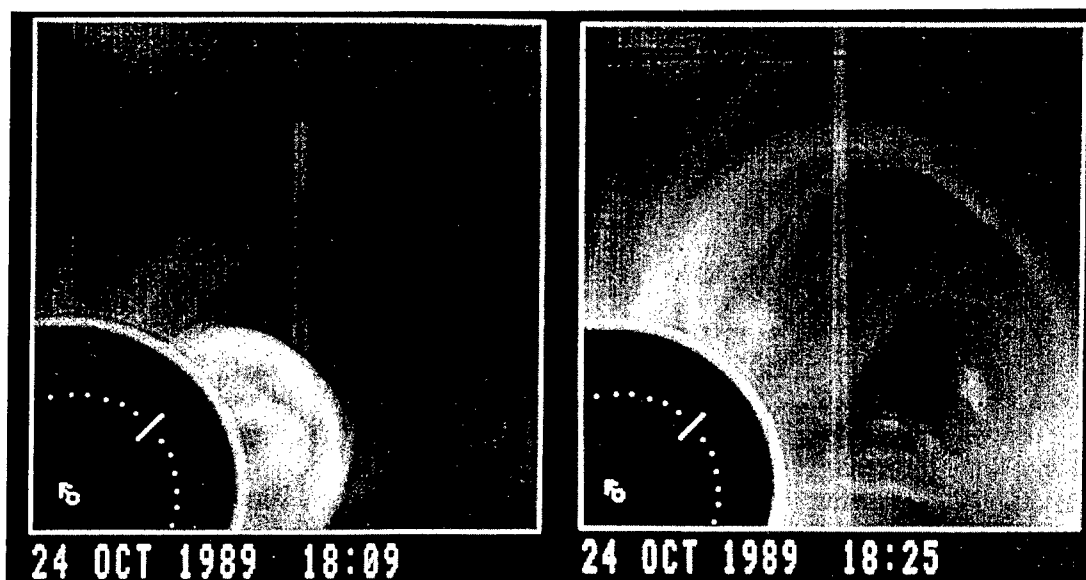

Fig. 2. The solar proton event of 24 October 1989.

Fig. 3. The coronal mass ejection (CME) associated with the solar proton event of 24 October 1989 as observed by the SMM cronograph. (Figure courtesy A. Hunthausen, HAO).

Interplanetary Shock Dominated Events

The interplanetary shock dominated events are those associated with solar activity near the central meridian of the sun (presumably the result of a very fast coronal mass ejection) and the resulting powerful fast interplanetary shock directed toward the observer that continues to accelerate particles at the shock front that propagates along the pre-existing interplanetary field lines toward the observer. In these cases the maximum flux is observed as the shock front (the particle acceleration source) passes over the ob-

explain the solar proton fluence observed at the Earth on 4 August 1972. Figure 5 illustrates the solar proton intensity-time profile measured in early August 1972 by two spacecraft; the >14 MeV proton flux observed on Pioneer 9 (located at 0.77 AU, 46° east of the Earth-Sun line) and the >10 and >30 MeV proton flux observed at 1AU by the Earth-orbiting IMP 4 spacecraft. The time of the shock impact on the Earth's magnetosphere is denoted by the ∇ character in this figure. Note that the very high flux values are only present during the time interval between the successive interplanetary shocks.

The speed profile of the interplanetary shocks (in the solar wind frame) has been modeled as radially propagating blast waves by Smart and Shea (1985). Smart, Shea and Webber (1990) examined the proton flux profiles and the time of the shock passage and concluded that local acceleration was responsible for the observed flux profile. The blast wave model parameters and shock passage recorded by the various spacecraft are listed in Table 1. Figure 5 illustrates the effects of shock acceleration seen in the Pioneer 9 data on 3 August by the flux level before and after the shocks arrive at this spacecraft. In this case, the flux level increased approximately a factor of three. This is typical for strong shocks and has been observed many times. A different profile is observed at the Earth which happens to be positioned between converging shocks on 4 August.

Table 1.   Parameters for the August 1972 shock events. [From Smart, Shea and Webber (1990).]

Blast Wave Equation	Pioneer 9 (R = 0.77 AU, ESP = -46°) Shock Arrival	Earth (R = 1 AU, ESP = 0°) Shock Arrival	Poineer 10 (R = 2.2 AU, ESP = –45°) Shock Arrival
$V = 516\,R^{-0.5}$	3 Aug 0440 UT	4 Aug 0119 UT	6 Aug 1520 UT
$V = 623\,R^{-0.5}$	3 Aug 1117 UT	4 Aug 0221 UT	6 Aug 2230* UT
$V = 1275\,R^{-0.5}$	4 Aug 2323 UT	4 Aug 2054 UT	6 Aug 2230* UT

* merged shocks

In the blast wave equation, V is speed in km s⁻¹; R is radial distance from the sun in AU; ESP is Earth-Sun-Probe angle, positive in the direction of solar rotation.

The data in Table 1 shows that the Earth was between two converging interplanetary shocks when the extremely large flux maximum was observed at the Earth on 4 August 1972. The three distinct interplanetary shocks observable at 0.77 AU and 1.0 AU had merged into two by 2.2 AU. Inspection of Figure 5 illustrates that the very high proton fluxes were only observed in the interval between the two converging shocks. Furthermore, the very high flux values observed at the Earth were not observed at Pioneer 9 at 0.77 AU. The Pioneer 9 proton flux data on 4 August have been viewed with some skepticism precisely because the flux measured on Pioneer 9 is not what would be expected from the relative positions of the two measurement locations with respect to the solar activity on 4 August. However, the Pioneer data are considered valid for scientific analyses before the August 1972 events and are considered valid for scientific analyses after the August 1972 events. We suggest that the Pioneer 9 data is also valid during the August 1972 events. This data suggests that the flux maximum observed at the Earth was a local spatial phenomenon limited to the domain between the two converging shocks, and that a classical power law radial extrapolation of the flux observed at the Earth to other distances is not warranted.
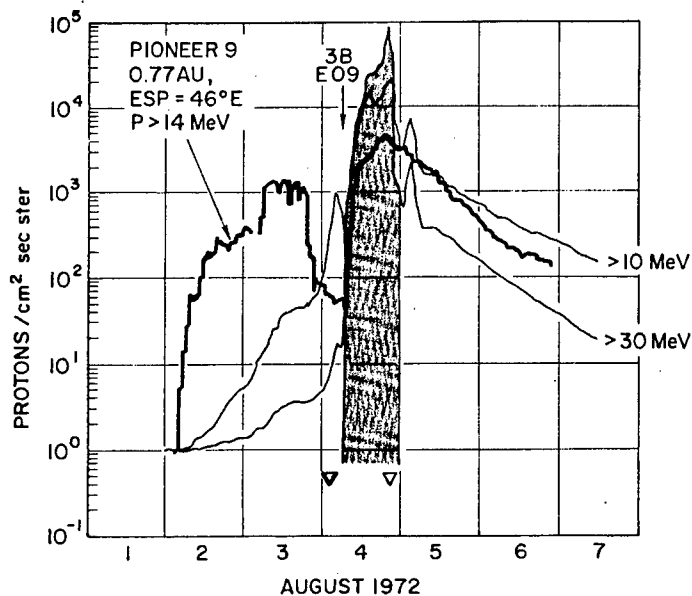
Fig. 5. The proton events of August 1972 as observed on Pioneer 9 and the Earth. The symbol ∇ indicates the shock arrival time at the Earth. The notation 3B, E 09 designates the location of associated solar flare activity.

CONCLUSIONS

We have divided the solar particle events into two general classes, near-sun injection and interplanetary-shock dominated events. The events dominated by a near-sun injection of particles onto interplanetary magnetic field lines leading to the spacecraft position represent the "classical" solar particle event associated with solar activity. This class of event scales in radial distance by the classical power law extrapolation. The interplanetary shock dominated events generates a maximum flux as the shock passes the detection location but the flux does not scale in the classical manner with radial distance. These two classes of events must be considered when estimating the possible solar proton flux encountered in interplanetary space during a manned Mars mission.

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